

The faintest galaxies

Stefania Salvadori* and Andrea Ferrara†

**Kapteyn Astronomical Institute, Landleven 12, 9747 AD Groningen, The Netherlands*

†*Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy*

Abstract. We investigate the nature of Ultra Faint dwarf spheroidal galaxies (UF dSphs) in a general cosmological context, simultaneously accounting for various “classical” dSphs and Milky Way (MW) properties, including their Metallicity Distribution Function (MDF). The model successfully reproduces both the observed [Fe/H]-Luminosity relation and the mean MDF of UFs. According to our results UFs are the living fossils of H_2 -cooling minihaloes formed at $z > 8.5$, i.e. before the end of reionization. They are the oldest and the most dark matter-dominated ($M/L > 100$) dSphs in the MW system, with a total mass of $M = 10^7\text{--}10^8 M_\odot$. The model allows to interpret the different shape of UFs and classical dSphs MDF, along with the frequency of extremely metal-poor stars in these objects. We discuss the “missing satellites problem” by comparing the UF star formation efficiencies with those derived for minihaloes in the Via Lactea simulation.

Keywords: <Enter Keywords here>

PACS: 98.35.Ac

Ultra faint dwarf spheroidal galaxies (UF dSphs) represent the *least* luminous ($L < 10^5 L_\odot$), the *least* metal-rich ($\langle [Fe/H] \rangle < -2$) and probably the *least* massive ($M < 10^8 M_\odot$) stellar systems ever known. Such extreme features make these galaxies the best suitable living fossils for the investigation of the early cosmic star formation. In addition, recent surveys of very metal-poor stars in dSphs pointed out that $[Fe/H] < -3$ stars represent the 25% of the total stellar mass in UFs [9], while they are greatly rare [16] in “classical” dSphs. When do UFs form? Could these galaxies represent the first star-forming objects in the MW system?

In this contribution we investigate the nature of UFs from a general cosmological prospective. To this aim we use the semi-analytical code GAMETE (GalaxyMErgerTree&Evolution), which traces the hierarchical build-up of the Milky Way (MW) system, simultaneously accounting for various classical dSphs and MW properties, including their Metallicity Distribution Functions (MDFs).

Star formation and feedback processes

The basic features of the model can be summarized in few points (for a complete description see [11, 12, 13]). After having reconstruct a statistical significant sample of MW hierarchical merger histories we follow the evolution of gas and stars along each hierarchical tree by assuming that: (i) stars can only form in objects above a minimum halo mass, $M_{sf}(z)$, whose evolution (Fig. 1, left panel) accounts for the suppression of star formation (SF) in progressively more massive objects due to radiative feedback effects [13]; (ii) the reionization of the MW environment is complete at $z_{rei} = 6$; (iii)

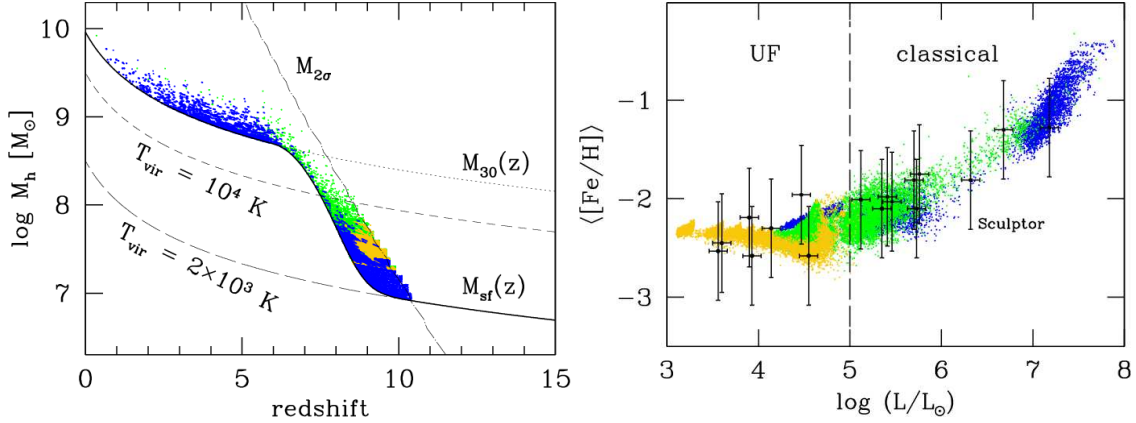


FIGURE 1. Selected dSph candidates (points) in 10 possible merger histories. Different colors show the baryonic fraction f_b at the formation epoch with respect to the cosmic value $f_c = 0.156$: $f_b/f_c > 0.5$ (blue), $0.1 < f_b/f_c < 0.5$ (green), $f_b/f_c < 0.1$ (yellow). We show: *Panel a*: the dSph hosting halo mass and circular velocity as a function of the formation redshift z . The lines in the panel show the evolution of $M_{sf}(z)$ (solid), the halo mass corresponding to 2σ peaks (dotted-long dashed), $T_{vir} = 10^4 K$ (short dashed line) and $T_{vir} = 2 \times 10^3 K$ (long dashed line). *Panel b*: the total luminosity of dSphs as a function of their iron-abundance (points). Points with error bars are observational data ([9]).

in each galaxy the SF rate is proportional to the mass of cold gas, whose gradual accretion is regulated by a numerically calibrated infall rate [8]; (iv) due to ineffective cooling by H_2 molecules the SF efficiency in “minihaloes” ($T_{vir} < 10^4 K$) is reduced $\propto [1 + (T_{vir}/2 \times 10^4 K)^{-3}]^{-1}$ with respect to H-cooling haloes.

The chemical enrichment of the gas is followed both in proto-Galactic haloes and in the MW environment by taking into account the mass-dependent stellar evolutionary timescales and the effects of mechanical feedback due to supernova (SN) energy deposition [12]. The free parameters of the model (SF and SN wind efficiencies) are calibrated to *simultaneously reproduce* [11] the global properties of the MW (stellar/gas mass and metallicity) and the MDF of Galactic halo stars [15, 14].

The satellite candidates

The dSph candidates are selected among the star forming haloes ($M > M_{sf}(z)$) which are likely to become satellites i.e. those corresponding to density fluctuations $< 2\sigma$ [2]. Their total dark matter (DM) mass, formation redshift and initial baryonic fraction (f_b) with respect to the cosmic value $f_c = \Omega_b/\Omega_m = 0.156$ are shown in Fig. 1 (left panel). Gas-rich systems, $f_b/f_c > 0.5$, are newly virialized objects accreting gas from the MW environment; intermediate (gas-poor) systems, $0.1 < f_b/f_c < 0.5$ ($f_b/f_c < 0.1$), originate from the mixed merging of star-forming (newly virializing) and starless progenitors; their smaller baryonic content is the result of shock-heating of the infalling gas during major merging events [3]. According to our results dSph galaxies are hosted by DM haloes with masses $M \approx 10^{7-9} M_\odot$, virialized out of the MW environment between $z \approx 10.5$ and $z \approx 3$.

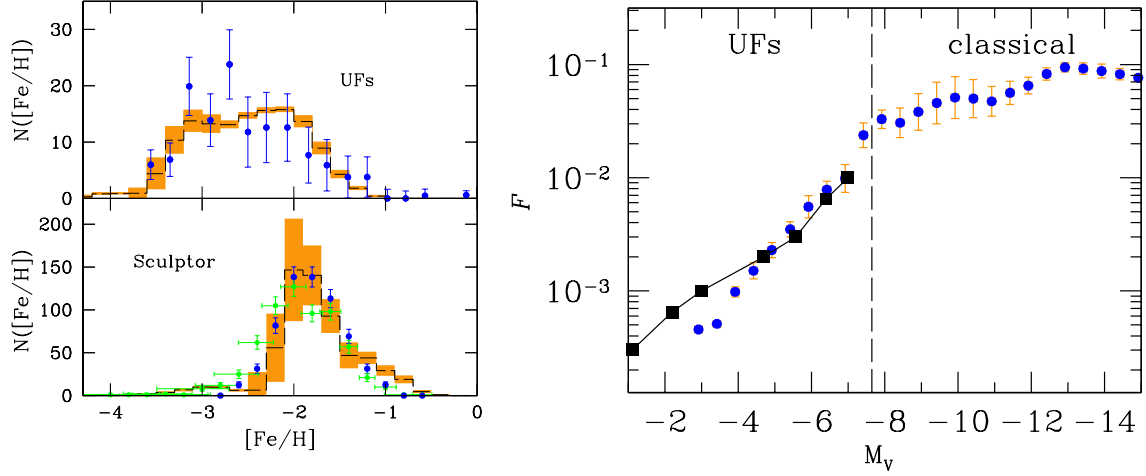


FIGURE 2. *Left panels:* observed (points) and simulated (histogram) MDF of UFs (*top*) and Sculptor dSph (*bottom*). Histograms are the averaged MDF over all UFs ($L < 10^5 L_\odot$ *top*) and Sculptor ($10^6 L_\odot < L < 10^{6.5} L_\odot$ *bottom*) candidates in 10 merger histories. The shaded area is the $\pm 1\sigma$ scatter among different realizations. The data points are by [9] (*top*, Poissonian errors) and by the DART team (*bottom*) using the old (blue points, Poissonian errors [7]) and the new (green points, observational errors [16]) CaT line calibration. *Right panel:* fraction $\mathcal{F} = M_*/f_c M$ of the potentially available cosmic baryons turned into stars as a function of M_V . The points are the average over all dSph candidates in 10 realizations. Error bars show the $\pm 1\sigma$ dispersion among different dSphs. The squared points are the results by [6]

The Fe-luminosity relation

The observed Fe-Luminosity relation of dSph galaxies is well reproduced by the model (Fig. 1, right panel). We found that minihaloes predominantly populate the faint end of the relation, $L < 10^6 L_\odot$ while above that luminosity H-cooling haloes dominates. We therefore conclude that *all UFs are left-overs of H2-cooling minihaloes*, in good agreement with the findings by [1]. As minihaloes virialized when $z > 8.5$ and have total masses $M \approx 10^7\text{--}10^8 M_\odot$ (left panel), we infer that *UFs are the oldest and the more DM dominated ($M/L > 100$) dSphs in the MW system*. In the faintest UFs, $L < 10^4 L_\odot$, which are gas poor systems, the mass-to-light ratio reach extreme values such as $M/L \approx 10^4$.

Metallicity Distribution Functions

The observed and simulated MDFs of UFs ([9]) and Sculptor dSph ([7, 16]) are compared in Fig. 2 (left panels). The UFs MDF is broader with respect to the Sculptor MDF because of their more prolonged SF history [13], while it is shifted towards lower [Fe/H] values as a result of the lower metallicity of the MW environment at the time of their formation: Sculptor-like dSphs are associated with gas-rich, H-cooling haloes, that virialize at $z \approx 7.5$, when the *pre-enrichment* of the MW environment was $[\text{Fe}/\text{H}] \approx -3$ ([12]); UFs instead form at higher redshifts ($z > 8.5$) when the metallicity was lower. Note the small $[\text{Fe}/\text{H}] < -3$ tail in Sculptor predicts by the model and now confirmed

by the new results of the DART survey [16] (see the Figure) and by high resolution spectroscopic studies [4]. In our picture these stars are found to be stellar relics of the rare SF episodes occurred in some progenitor minihaloes, when $z > 7.5$. This implies that $[\text{Fe}/\text{H}] < -3$ stars in classical dSphs are expected to have the same abundance pattern of that in UFs [13]. Recent high-resolution analysis of extremely iron-poor stars in Sculptor [5] and UFs [4, 10] have confirmed this prediction.

Are there missing satellites?

The fraction of the potentially available cosmic baryons turned into stars by $z = 0$ ($\mathcal{F} = M_*/f_c M$) is shown in Fig. 3, as a function of the dSph magnitude, M_V . Model results are compared with the findings of [6], which determine \mathcal{F} for minihaloes by matching the luminosity function of the MW satellites in the SDSS. The agreement between the two studies is very good. Hence, although our method prevents us from making specific predictions on the actual number of satellites, we conclude that *there is no missing satellites problem in terms of SF efficiency*.

Conclusions

Ultra Faint dSphs are the today-living counterpart of high redshift, H_2 -cooling minihaloes. They are the oldest ($z > 8.5$) and more DM dominated ($M/L > 100$) galaxies in the MW system. They are very ineffectively SF objects, turning into stars $< 3\%$ of the potentially available cosmic baryons. The higher fraction of $[\text{Fe}/\text{H}] < -3$ stars in UFs, with respect to classical dSphs, reflects both their lower SF rate, caused by ineffective H_2 cooling, both the lower metal (pre-)enrichment of the MW-environment at their (further) formation epoch. At the moment, these faint galaxies represent the best available living fossil to investigate the early cosmic star formation.

REFERENCES

1. M. Bovill & M. Ricotti, *ApJ*, **693**, 1859, 2009
2. J. Diemand, P. Madau, B. Moore *MNRAS*, **364**, 367, 2005
3. T. J. Cox, J. Primack, P. Jonsson & R. S. Somerville, *ApJ*, **607**, L87, 2004
4. A. Frebel et al., *ApJ*, **708**, 560, 2010
5. A. Frebel et al., *Nature* in press
6. P. Madau et al., *ApJ*, **689**, L41, 2008
7. A. Helmi et al., *ApJ*, **651**, L121, 2006
8. D. Z. Kereš, N. Katz, D. H. Weinberg, R. Dave, *MNRAS*, **363**, 2, 2005
9. E. N. Kirby, J. D. Simon, M. Geha, P. Guhathakurta. & A. Frebel, *ApJ*, **685**, L43, 2008
10. A. Koch et al. *A&A*, **506**, 729, 2009
11. S. Salvadori, R. Schneider & A. Ferrara, *MNRAS* **381**, 647, 2007
12. S. Salvadori, A. Ferrara & R. Schneider, *MNRAS* **386**, 348, 2008
13. S. Salvadori & A. Ferrara, *MNRAS* **395**, L6, 2009
14. S. Salvadori, A. Ferrara, R. Schneider, E. Scannapieco & D. Kawata *MNRAS*, **401**, L5, 2010
15. T. Schoerck et al. *A&A*, **507**, 817, 2009
16. E. Starkenburg et al. *A&A*, **513**, A34, 2010